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COMBINED LOADING OF A WAVE AND SURFACE CURRENT ON A FIXED VERTICAL SLENDER CYLINDER

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KEYWORD

Layered current, Wave-current interaction, Wave-current loading, Moment, Nonlinear 3D flow field, Vertical fixed slender cylinder

ABSTRACT

A study on the loading of an oblique surface wave and a surface current field on a fixed vertical slender cylinder in a 3D flow frame is illustrated in the present paper. The three dimensional expressions describing the characteristics of the combined wave-current field in terms of mass, momentum and energy flux conservation equations are formulated. The parameters before the interaction of the oblique wave-free uniform current and current-free wave are used to formulate the kinematics of the flow field. These expressions are also employed to formulate and calculate the loads imparted by the wave-current fluid flow on a bottom mounted slender vertical cylinder. The surface current considered in this report, is assumed uniform and acting over a layer of fluid that extends from the free surface to a specified finite depth. Prior work assumes that uniform currents existed over the total depth of the fluid domain. In this paper we extend the approach considered in Zaman and Baddour (2004) for the wave-current analysis. Morison et al equation is deployed for the load computations in all cases. The above model is utilized to compute the loads on a slender cylinder for a wave with varying range of incidence current field. Computations of the moments are also done for the case when current is existed over the whole water depth of the domain.

INTRODUCTION

Fluid motion in the sea is a blend of wave and current of different forms. The coexistence of waves and currents and consequently their interaction play an essential role in most ocean dynamic processes and are important topics for ocean engineers and related scientists. In order to evaluate the performance of any ocean structure it is an important task for the designer to account for the effects resulting from the interaction of a combined wave-current field with any ocean structure. The computation of loads exerted by waves and currents is an important task in the study of the stability/integrity of any ocean structure.

In the present formulation it is assumed that the flow fields are irrotational and inviscid. This allows the estimation of the flows characteristics needed in a Morison et al equation context. Velocity potentials are adopted to express the oblique flow fields in 3D for: (*i*) a wave field in the absence of current; (*ii*) a current field in the absence of wave and (*iii*) the wave-current combined field after the interaction of both a current-free wave and a wave-free current. These three distinct flow fields are first introduced for collinear flows in Baddour and Song (1990a and 1990b) and extended in 3D in Zaman and Baddour (2003).

For the computation of the parameters of the wave-current field, we have developed three-dimensional expressions describing the characteristics of the combined flow in terms of mass, momentum and energy transport conservation equations and the given before-interaction parameters of a wave-free uniform current and current-free wave. These equations are efficient in describing the combined wave-current field parameters. The relations obtained in satisfying the conservation of mass, momentum, energy flux and a dispersion relation generate a system of nonlinear equations that are solved to evaluate the sought-for wave-current flow parameters, namely, the free surface wave height, wavelength, current-like term and mean water depth after the interaction. In other words due to the presence of the current the location of the mean water level as well as other parameters of the combined wave-current field will change after the interaction such that to satisfy the conservation equation mentioned above. These equations and their solution were developed for the collinear case in Baddour and Song (1990a and 1990b). The concept was generalized for oblique waves in Zaman and Baddour (2002). The obtained model also encompasses the 2D case and is applicable to a current-free or a wave-free flow with appropriate boundary conditions.

Zaman and Baddour (2004) showed a comparison of the obtained results due to the present model to those obtained using three other models being used in the offshore industry is shown for a range of the normalized current parameters. One of these three models is proposed by the American Petroleum Institute (API, 1993), which is based on a superposition principle. In this case the current was assumed to exist along the whole water depth.

In the present study it is assumed that current is uniform and acting over a layer of fluid that extends from the free surface to a specified finite depth.

In this computation, we calculate the loads imparted by the fluid on a bottom mounted slender vertical cylinder representing a typical element of an offshore structure. The load computation uses Morison et al (1950) equation with appropriate drag and mass coefficients. See for example Chakrabarti (1987) and Sarpkaya and Isaacson (1981)).

Here the total load and moment are calculated from the effects of the combined wave-current field as proposed above and presented in Baddour and Song (1990a and 1990b) for the co-linear case and Zaman and Baddour (2002) for the oblique case.

MODEL FORMULATION

For the formulation it is assumed that a current-free monochromatic surface wave propagates on the surface of a water body in the direction given by $\vec{N}_w$ and that independently there exists a horizontal uniform wave-free current over the water depth extended from the free surface to a minimum finite depth identical to one half of the wavelength in the direction $\vec{N}_c$. When these two fields meet, see Figures 1a and 1b, a wave-current combined field develops in the direction $\vec{N}$, with a new set of unknown parameters namely, wave height, wavelength current parameter and water depth. These unknown parameters together with direction $\vec{N}$ are required to be computed from a system of conservation equations described in the next section. We first formulate the potential of a wave-current field in a direction $\vec{N}$.

Figure 1a shows the plan view of the computational domain with O the origin of the 3D inertial frame. The x and y axes subtend the horizontal plane, and z the vertical axis is perpendicular at O to both x and y, and points towards the reader. The unit vectors $\vec{N}_c$, $\vec{N}_w$ and $\vec{N}$ denote the directions of the wave-free current, current-free wave and wave-current fields, respectively. The unit vector $\vec{S}$ is normal to $\vec{N}$. On the other hand Figure 1b demonstrates a cross sectional view at location O before and after the interaction.

Assuming inviscid and incompressible fluid flows we conceive that the result of the interaction between a current-free wave field (wave celerity is C_o) in direction $\vec{N}_w$ with a wave-free current (current velocity is U_o) in direction $\vec{N}_c$ exists and is here called a wave-current flow field in the $\vec{N}$ direction. A velocity potential is assumed hence to exist and is used to describe this combined wave-current field. It is given by the following expression to second order in the surface undulation amplitude:

$$\Phi(x,y,z,t) = \vec{U}\cdot\vec{x} + \frac{a_1}{k\sinh kd}\left(\sigma - \vec{U}\cdot\vec{k}\right)\cosh k(d+z)\sin(\vec{k}\cdot\vec{x}-\sigma t) + \frac{1}{k\sinh 2kd}\left(a_2 - \frac{1}{4}a_1^2 k\coth kd\right)\left(\sigma-\vec{U}\cdot\vec{k}\right)* \cosh 2k(d+z)\sin 2(\vec{k}\cdot\vec{x}-\sigma t) + O(k^3a^3) \tag{1}$$

where $U = \left|\vec{U}(U_x, U_y)\right|$ is the current-like parameter and $k = \left|\vec{k}(k_x, k_y)\right|$ is the wave number whose related vector is normal to the surface undulation front in the wave-current field and lies in the horizontal x-y plane, σ is the angular frequency, a the amplitude of the surface disturbance in the wave-current field, C the combined flow surface undulation celerity, d the mean water depth, t the time, $\vec{x}(x,y)$ the horizontal position vector of a point in the field and z is the vertical axis measured vertically upward from the still water level. The first and second order surface elevation amplitudes are given by a_1 and a_2, respectively. See for example Dean and Dalrymple (1992) for the first order 2D collinear case, and Baddour and Song (1990b) for the second and higher order collinear case.

Equation 1 is a generalized form of the velocity potential. When the current parameter is null in equation 1 then it becomes the velocity potential of a current-free wave field and similarly when the wave parameter such as wave amplitude is non-exist then equation 1 turns into the velocity potential of a wave-free current field. For different forms of the velocity potential see Zaman and Baddour (2003).

The relation of the wave number and the angular frequency of the combined wave-current field is given by the following Doppler relation:

$$\sigma - \vec{U}\cdot\vec{k} = \sigma_r \tag{2}$$

where the relative angular frequency in the above equation is described by the following equation:

$$\sigma_r = \sqrt{gk\tanh kd} \tag{3}$$

The dispersion relation for the combined wave-current field is hence:

$$\left(\sigma - \vec{U}\cdot\vec{k}\right) = \sqrt{gk\tanh kd} \tag{4}$$

The periodic free surface elevation η is expressed to first order in amplitude a as:

$$\eta = a\cos(\vec{k}\cdot\vec{x}-\sigma t)+O(a^2) \qquad (5)$$

FLUID KINEMATICS

The particle velocity and acceleration components in the x, y and z direction in the combined wave-current field, current-free wave field and wave-free current field are discussed in details in Zaman and Baddour (2004).

Using equation (1) the particle velocity components in the x, y and z directions for combined wave-current field can be given by the following equations:

$$\begin{aligned} u_{x-wc} &= U_x + \frac{a_1\sigma_r}{\sinh kd}\frac{k_x}{k}\cosh k(d+z)\cos(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{2\sigma_r}{\sinh 2kd}\frac{k_x}{k}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\cosh 2k(d+z) \\ &\quad \cos 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (6)$$

$$\begin{aligned} u_{y-wc} &= U_y + \frac{a_1\sigma_r}{\sinh kd}\frac{k_y}{k}\cosh k(d+z)\cos(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{2\sigma_r}{\sinh 2kd}\frac{k_y}{k}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\cosh 2k(d+z) \\ &\quad \cos 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (7)$$

$$\begin{aligned} u_{z-wc} &= \frac{a_1\sigma_r}{\sinh kd}\sinh k(d+z)\sin(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{2\sigma_r}{\sinh 2kd}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\sinh 2k(d+z) \\ &\quad \sin 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (8)$$

The corresponding acceleration components in the x, y and z directions in the combined wave-current field are evaluated as:

$$\begin{aligned} a_{x-wc} &= \frac{a_1\sigma_r\sigma}{\sinh kd}\frac{k_x}{k}\cosh k(d+z)\sin(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{4\sigma_r\sigma}{\sinh 2kd}\frac{k_x}{k}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\cosh 2k(d+z) \\ &\quad \sin 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (9)$$

$$\begin{aligned} a_{y-wc} &= \frac{a_1\sigma_r\sigma}{\sinh kd}\frac{k_y}{k}\cosh k(d+z)\sin(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{4\sigma_r\sigma}{\sinh 2kd}\frac{k_y}{k}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\cosh 2k(d+z) \\ &\quad \sin 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (10)$$

$$\begin{aligned} a_{z-wc} &= -\frac{a_1\sigma_r\sigma}{\sinh kd}\sinh k(d+z)\cos(\vec{k}\cdot\vec{x}-\sigma t)- \\ &\quad \frac{4\sigma_r\sigma}{\sinh 2kd}\left[a_2-\frac{1}{2}a_1^2 k\coth kd\right]\sinh 2k(d+z) \\ &\quad \cos 2(\vec{k}\cdot\vec{x}-\sigma t)+O(k^3a^3) \end{aligned} \qquad (11)$$

The pressure distribution in the wave-current field to second order is obtained from the dynamic free surface boundary condition as:

$$\begin{aligned} P &= -\rho g z - \frac{\rho g a^2 k}{2\sinh 2kd}\left[\cosh 2k(d+z)-1\right]+ \\ &\quad \rho g a\frac{\cosh k(d+z)}{\cosh kd}\cos(\vec{k}\cdot\vec{x}-\sigma t)+ \\ &\quad \frac{3\rho g a^2 k}{2\sinh 2kd}\left[\frac{\cosh 2k(d+z)}{\sinh^2 kd}\right]-\frac{\rho g a^2 k}{2\sinh 2kd} \end{aligned} \qquad (12)$$

FLUX EQUATIONS FOR THE WAVE-CURRENT FIELD

We can obtain the mass flux ($\vec{Q}_{wc}=Q_{wc}\vec{N}$) of the combined wave-current field through the following relation up to second order in amplitude a:

$$\vec{Q}_{wc} = \rho d\vec{U} + \frac{\rho a^2}{2}\vec{k}\left(C-\frac{\vec{U}\cdot\vec{k}}{k}\right)\coth kd + O(k^3a^3) \qquad (13)$$

The corresponding momentum flux ($\vec{M}_{wc}=M_{wc}\vec{N}$) of the combined wave-current field is given as follows:

$$\begin{aligned} \vec{M}_{wc} &= \frac{1}{2}\rho g a^2\left(\frac{1}{2}+\frac{2kd}{\sinh 2kd}+\frac{2\vec{U}\cdot\vec{k}}{\sigma_r}\right)\frac{\vec{k}}{k}+ \\ &\quad \frac{1}{2}\rho g d^2\left(1+\frac{2\left|\vec{U}\right|^2}{gd}\right)\frac{\vec{U}}{U}+O(k^3a^3) \end{aligned} \qquad (14)$$

In a similar fashion the net energy flux ($\vec{E}_{wc}=E_{wc}\vec{N}$) of the combined wave-current field is expressed as:

$$\begin{aligned} \vec{E}_{wc} &= \frac{\rho g\vec{U}}{2}a^2 + \frac{\rho\vec{U}d}{2}\left[\left|\vec{U}\right|^2+\frac{gk}{\sinh 2kd}a^2\right]+\frac{\rho g a^2}{4}\left[1+\frac{2kd}{\sinh 2kd}\right]\left[C_r+\frac{\vec{U}\cdot\vec{k}}{k}\right]\frac{\vec{k}}{k} \\ &\quad +\frac{\rho g a^2}{4\sigma_r}\left[2\vec{U}(\vec{U}\cdot\vec{k})+\vec{k}\left|\vec{U}\right|^2\right]+O(k^3a^3) \end{aligned} \qquad (15)$$

where $\vec{k}/k=\vec{N}$ and $\vec{U}/U=\vec{N}$.

Taking the time averages of the flux parameters of the current-free wave field, wave-free current field and wave-current field we can obtain a set of conservation equations in the $\vec{N}$ direction and another set of equations in the $\vec{S}$ direction. These two sets of equations along with equation (4) will give the solution of the unknown wave height, wavelength, current, mean water depth and the direction of the combined wave-current field. For details see Zaman and Baddour (2002).

LOADING ON A VERTICAL BOTTOM MOUNTED SLENDER CYLINDER

Forces due to combined wave-current field on the slender cylinder

Following Morison et al (1950) equations have been used to compute forces and their moments about the sea bottom due to inertia and drag forces on a fixed vertical slender cylinder (see also for example Chakrabarti, (1987) and, Sarpkaya and Isaacson (1981)):

$$\vec{F}_I = C_M A_M \frac{D\vec{u}}{Dt} \tag{16}$$

$$\vec{F}_D = C_D A_D \vec{u}|\vec{u}| \tag{17}$$

where $A_M = \frac{\rho\pi}{4} D^2$, $A_D = \frac{\rho}{2} D$; C_M and C_D are inertia and drag coefficients, ρ the fluid density and D is the diameter of the cylinder. $D/Dt = \partial/\partial t + u\,\partial/\partial x + v\partial/\partial y + w\,\partial/\partial z$ is the time derivative, where u, v and w are the particle velocity components of $\vec{u}$ in the x, y and z directions, respectively, and appropriate to the associated flow fields, namely: wave, current and wave-current fields.

The coefficients C_M and C_D are obtained for a specific Keulegan-Carpenter number (*KC*) from the curve proposed by Iwagaki et al (1983) partially shown in Figure 2.

The total load $\vec{F}_t$ is then obtained from the summation of the inertia and the drag forces as:

$$\vec{F}_t = \vec{F}_I + \vec{F}_D \tag{18}$$

where $\vec{F}_I$ is the force due to inertia and $\vec{F}_D$ is the force due to drag.

Moment due to combined wave-current field on the slender cylinder about the bottom

Moment is computed for the case of a uniform current distribution across the water depth. Here the current depth that extents from the free surface to a finite depth is expressed by $d_u/d=1$, *see* Figure 1b.

The following equation is utilized in this case to compute the moment on the cylinder:

$$M = \int_{-d}^{\eta} \Delta\vec{F}_t \cdot (d+z)dz \tag{19}$$

where $\Delta\vec{F}_t$ is the force/unit length of the cylinder and M is the moment due to the force about the bottom of the cylinder, positive in the clockwise direction.

COMPUTATIONAL PROCEDURE

In the present computations, the total loads are calculated from the effects of the combined wave-current field. The first step is to use equations (6) to (11) and equations (13) to (15) to predict the wave-current parameters that define the wave-current field. The second step in the computation is then to use equations (16) to (19) to produce the total load exerted on the cylinder by the combined wave-current field obtained in the first step.

CASE STUDY

As an example, the established models have been applied for the computation of loads for a collinear or 2D case and for an oblique or 3D case. For both examples, it is assumed that a monochromatic current-free surface wave interacts with a normalized wave-free uniform current U_o/C_o varying over the range of an opposite current to a range of following currents. It is also assumed that the surface current is uniform and acting over a layer of fluid that extends from the free surface to a specified finite depth. The extent of this layered-current is defined by the ratio of the layered-current depth, d_U to the mean water depth, d and may be described by the ratio d_U/d. See Figure 1b. The wave and current parameters used in this study are shown in Table 1. Subscript 0 denotes a value of a parameter before interaction. The diameter of the cylinder is 35cm in all computations.

Table 1. Computational parameters

Parameters	2D Model	3D Model
U_o/C_o *(Maximum opposing)*	-0.2	-0.2
U_o/C_o *(Maximum following)*	0.572	1.359
H_o/L_o	0.01	0.01
d_o/L_o	2.0	2.0
d_U/d *(Maximum)*	1.0	1.0
d_U/d *(Minimum)*	0.25	0.25
Wave incident direction	0^o	10^o
Current incident direction	0^o	15^o

Descriptions of maximum and minimum loads obtained by above model for 2D collinear, non-oblique case are given in Figure 3 and Figure 4, respectively. In the 2D case we have found that the monochromatic wave that we have used in our computation, becomes O(10^{-4}m) (w.r.t. incident wave) when normalized current parameter reaches the value U_o/C_o = 0.571633 for the case of a wave with a following current. For the case when wave and current are in opposite directions the maximum wave height is reached at U_o/C_o = -0.2. Maximum wave height is reached due to wave blocking. At this point wave steepness exceeds the allowable breaking value (~0.14 in deep water) and the numerical model is stopped. These limits are shown in Figure 3 and in Figure 4 by a vertical dotted line.

The analyses and comparisons of loads for 2D non-oblique case are made at these two points, that is, when U_o/C_o = 0.571633 and U_o/C_o = -0.2. In the figures and tables F_t stands for the total force due to combined wave-current field or due to wave-free current field. F_w and M_w respectively, describe the absolute force and absolute moment due to the current-free wave field. The above results are summarized in Table 2.

Table 2. Loads for 2D case: wave with following current

Load	U_o/C_o	F_t/F_w	M_t/M_w
Maximum	0.571633	5.614554	-5.62134
Minimum	0.571633	5.614183	-5.62134

On the other hand when wave and current are in opposite directions the maximum and minimum loads obtained at U_o/C_o = -0.2 are shown in Table 3.

Table 3. Loads for 2D case: wave with opposing current

Load	U_o/C_o	F_t/F_w	M_t/M_w
Maximum	-0.2	10.02994	-10.012
Minimum	-0.2	-10.3892	10.407

It is important to mention here that when wave and current are in the same direction the wave height reduces with current and disappears when the current is strong enough to eliminate the wave amplitude from the combined wave-current field. In the absence of wave(s) the model is still capable to compute the loading imparted by the wave-free current field. The continuation of the solid line in the figures after the vertical dotted line, describes the loading due to wave-free current field in this case.

The reason for such behavior is that the kinematics is computed from the combined wave-current field where the interaction of wave and current is taken into account. This produces a significant change in wave heights and wavelengths. It is evident that a following current reduces the wave heights and increases the wavelengths. A substantial increase in wave heights and decrease in wavelengths are observed in the waveform for the case of an opposite current. Hence for the case of a wave interacting with a reverse current, the increase in the wave heights is considered to be responsible for the rapid increase of the loads in a combined wave-current field.

For the oblique interaction cases the above mentioned wave and current conditions are used (as shown in Table 1) and in addition, it is assumed that the wave enters the computational domain at an oblique angle of 10^o, while the current is at an angle of 15^o with the positive direction of the x-axis. Figures 5 and 6 demonstrate the comparison between the maximum and minimum loads obtained by the above four models in the oblique 3D field. In the 3D oblique case, the analyses and comparisons of loads are also made at two points, at U_o/C_o = 1.359785 when surface undulation disappeared due to current action for a wave with a following current and at U_o/C_o = -0.2 when the wave is in opposite direction of the current shown by vertical dotted line in Figures 5 and 6. Table 4 presents the maximum and minimum loads for U_o/C_o = 1.359785 when surface undulation becomes O(10^{-4}m) (w.r.t. incident wave) due to current action.

Table 4. Loads for 3D case: wave with following current

Load	U_o/C_o	F_t/F_w	M_t/M_w
Maximum	1.359785	26.28006	-27.4581
Minimum	1.359785	23.85693	-27.4581

On the other hand when wave and current are in opposite directions the maximum and minimum loads obtained at U_o/C_o = -0.2 are summarized in Table 5. For the 3D oblique case we have not proceeded after U_o/C_o = 1.359785 since wave height at this current becomes O(10^{-4}m).

Table 5. Loads for 3D case: wave with opposing current

Load	U_o/C_o	F_t/F_w	M_t/M_w
Maximum	-0.2	6.21917	-6.29528
Minimum	-0.2	-6.57534	6.65449

Figures 7 and 8 respectively, show the moment for 2D and 3D flow fields computed by equation (19) for the cases when waves coexist with a current that extents from the free surface to the bottom in the domain. In the figures total moment due to combined wave-current field M_t is normalized by the moment due to wave M_w.

CONCLUSION

A numerical model has been developed using three-dimensional expressions describing the characteristics of the combined wave-current field in terms of mass, momentum and energy flux conservation equations. This model is then employed for the computation of wave-current field total loading on a slender vertical cylinder in the 3D flow field. Four different categories of current field considering its extent from the free surface to a certain water depth are used in the numerical computation. The absolute value of the loading of the respective current-free wave has been used to normalize all forces and moments obtained from this model. It is observed as expected that load on the vertical cylinder is directly proportional to d_U/d ratios, *i.e.* when d_U/d is greater the loading on the cylinder is also larger. Moments due to combined wave-current field are also computed for wave with varying currents that exist all over the water depth. Examples for collinear 2D non-oblique waves and currents and an oblique 3D case are shown. It is worthwhile to mention here that for the case of wave with following current, even when waves disappear due to strong current, the present model is still applicable for the computation of loading due to current only.

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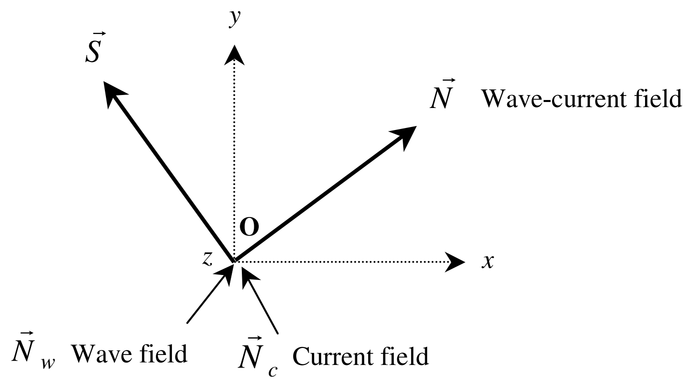

Figure 1a Wave-free current, current-free wave and wave-current fields relative directions

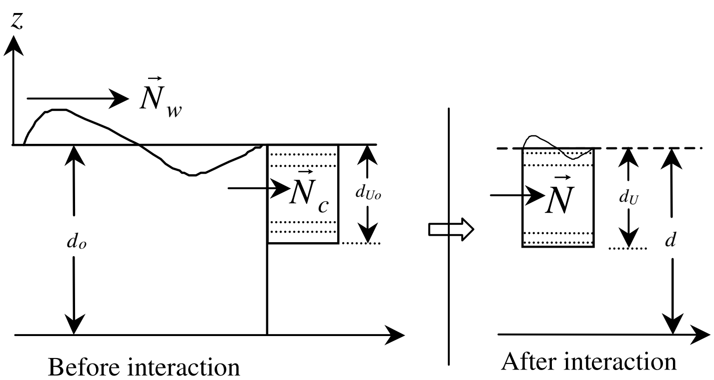

Figure 1b 2D schematic view of wave-free current and current-free wave field before interaction and combined wave-current field after interaction.

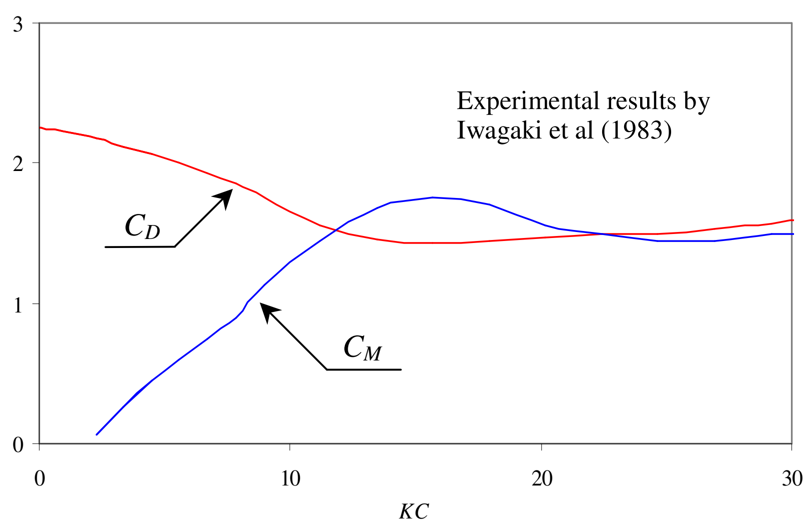

Figure 2 Relation between KC and, C_M and C_D (Partial)

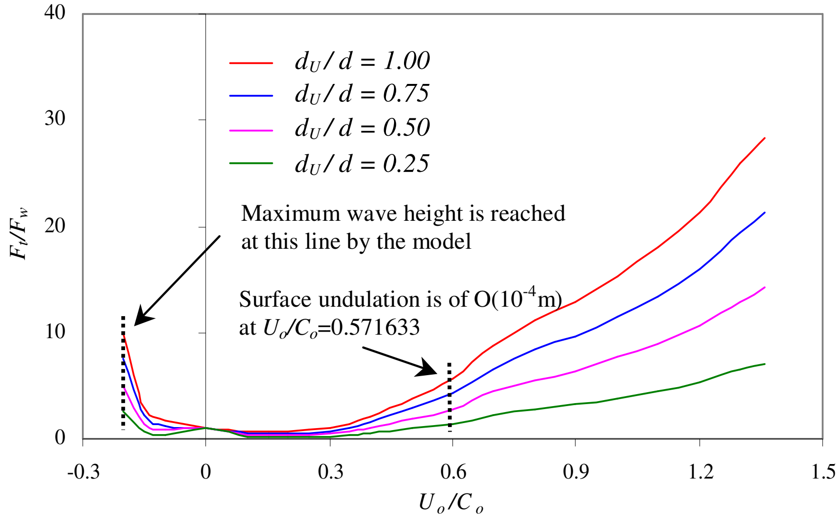

Figure 3 Normalized maximum exerted forces computed by the *Model* for different layered currents in 2D flow

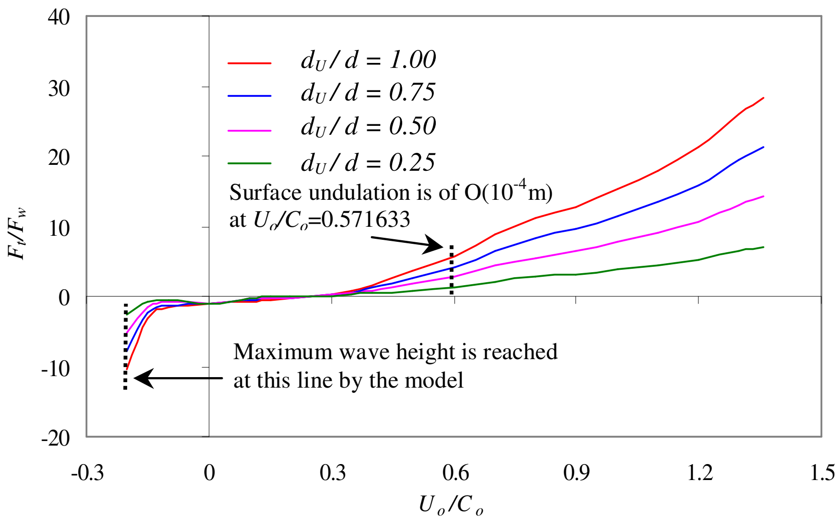

Figure 4 Normalized minimum exerted forces computed by the *Model* for different layered currents in 2D flow

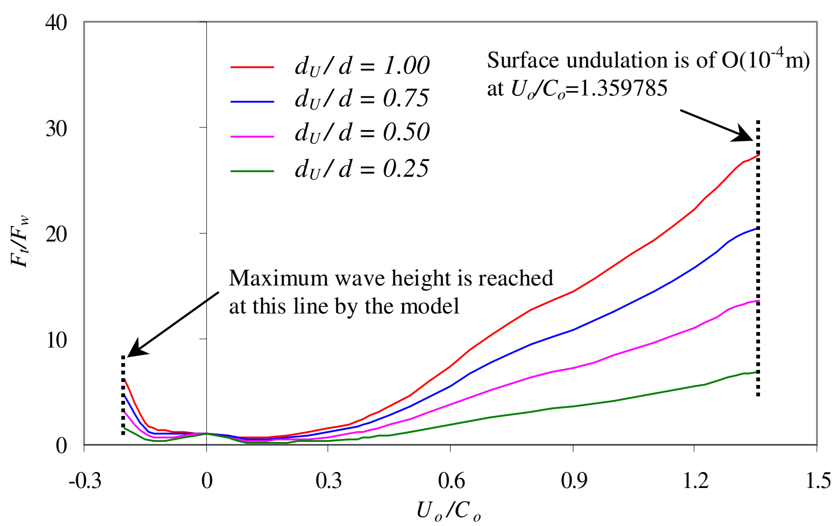

Figure 5 Normalized maximum exerted forces computed by the *Model* for different layered currents in 3D flow

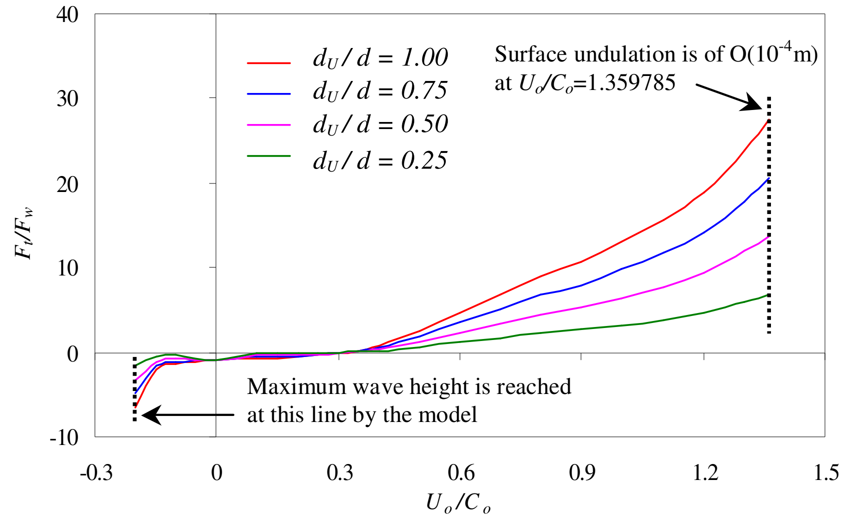

Figure 6 Normalized minimum exerted forces computed by the *Model* for different layered currents in 3D flow

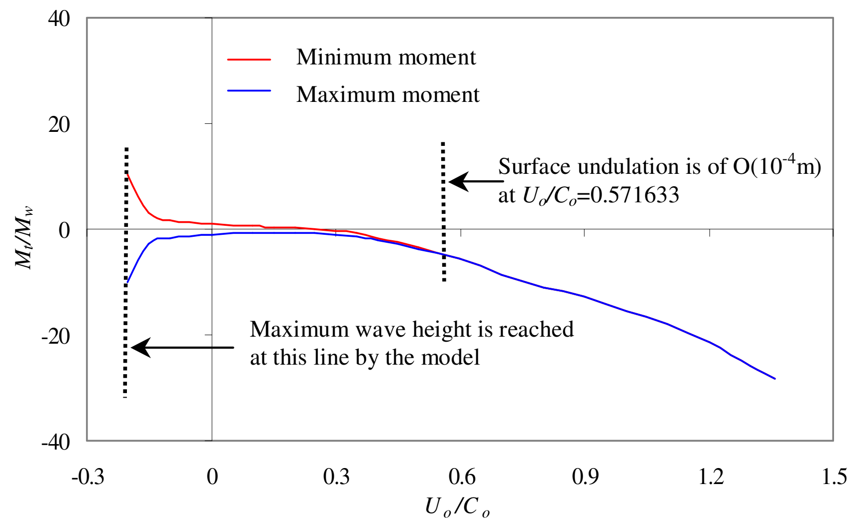

Figure 7 Normalized maximum and minimum moments computed by the model in 2D flow

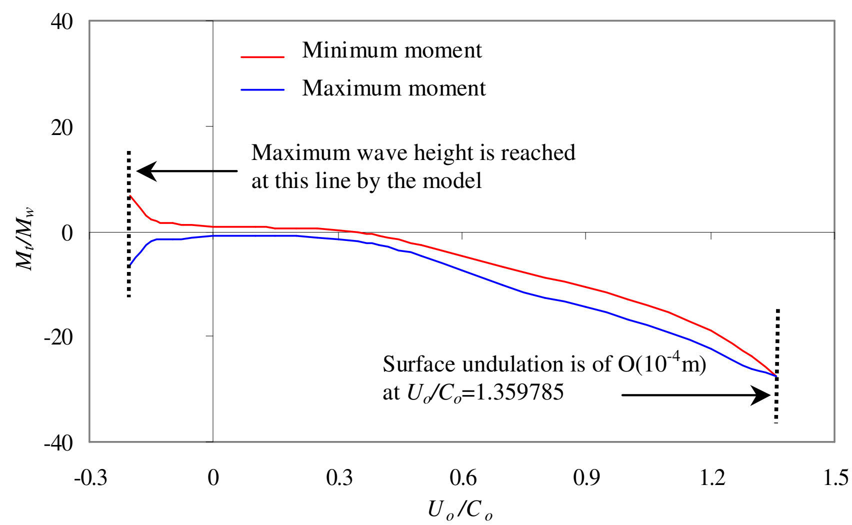

Figure 8 Normalized maximum and minimum moments computed by the model in 3D flow